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Cognitive Approaches to Automated Engineering Design

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Summary

This project set out to explore fundamental cognitive-based mechanisms in design innovation. Its emphasis focsued on the organizational basis to support innovation. Our approach combined cognitive studies, agent-based computational simulations, and modeling of the design process. Fundamentally our work provides the basis to better understand the innovation process and to development methods to improve that process. The original goal of the project was to explore both fundamental cognitive mechanisms for creative design and computational tools that would enable engineers to improve their design process through intelligent agent-based strategies (using some findings from the cognitive work). Due to a reduced budget and new emphasis for the AFOSR program, the cognitive work was de-emphasized while the agent-based work was pursued.

An organization's design- the structuring of its resources and flows of knowledge- is an important element determining its effectiveness. An essential element to achieving an organization's problem-solving (and thus design) potential is the role that interdependence, in both the task and the organization of the team, plays in determining the dynamic and emergent system level properties of the organization and its effectiveness. In this project, we introduced a computational platform for experimentally investigating the structural dependencies found in the design of a complex system, and explored their role in determining system behaviors and performance. The approach developed is a multiagent simulation of the conceptual design of space mission plans by Team X, an advanced projects design group at NASA's Jet Propulsion Laboratory. The algorithm is composed of rich, descriptive models of both the team- types and timing of interactions, collaborative methods, sequencing, rates of convergence- and the task- primary variables, their behaviors and relations, and the approaches used to resolve them. The objective was to create an environment of interaction representative of that found in actual design sessions. Better understanding how the dynamics arising from team organizational and domain task interdependencies impact the team's ability to effectively resolve its task and should lead to the development of guidelines for better coping with task complexities, suggest ways to better design teams, as well as suggest ways for improving the search for innovative solutions.

In order to develop this simulation, a detailed study of Team X was performed, including observation of its conceptual design process that included tracking and classifying interactions between the different team members, interviews with team members about their interactions and job focus, and analytical models of aspects of their design tasks (such as the design of the thermal system for a spacecraft). 17 different participants were included (thermal, control, communications, etc.) [1]. These findings were then imbedded in a computational algorithm where 17 agents used various collaboration, negotiation and analysis strategies to determine spacecraft configurations to solve a mission task. The program, written in Java, includes over 1000 core variables and over 100,000 lines of code [2].

The program can be used for several tasks:

1. Generate spacecraft concepts – the method introduces a new, more intelligent approach to computational concept generation. Few, if any, design generation programs are as sophisticated in its knowledge base and methods as this program, at least at an academic level.

2. Organizational design – the program enables various structures and approaches to how agents are configured and how they interact. At a minimum it provides a model of a complex system, Team X; further it provides a means to understand and structure such systems.
3. Experimental exploration – the program enables variation of multiple input parameters that allows the investigation of how different methods effect design performance. The goal is to feed such findings back to design teams.
4. Exploration of underlying structure of network relationships – metrics can be developed that indicate the effectiveness of different agent structures [3].

Early in the project initial work in cognitive modeling of representations and how they influence design outcome was explored, in particular looking at the importance of expertise in reasoning level about engineering design tasks [4]. As engineers gain experience and become experts in their domain, the structure and content of their knowledge changes. Two studies were completed that examined differences in knowledge representation among freshman and senior engineering students. The first study examined recall of mechanical devices and chunking of components, and the second examined whether seniors represent devices in a more abstract functional manner than do freshmen. The most prominent differences between these two groups involve their representation of the functioning of groups of electromechanical components and how these groups of components interact to produce device behavior. Seniors are better able to construct coherent representations of devices by focusing on the function of sets of components in the device. The findings from these studies highlight some ways in which structure and content of mental representations of design knowledge differ during the early stages of expertise acquisition. This initial work provides evidence of the importance of understanding the structure and use of representation in the design process.

Personnel Supported

Faculty: Prof. Jonathan Cagan, Prof. Kenneth Kotovsky
Graduate students: Jesse Olson (full support: Mechanical Engineering student obtained PhD in May, 2006); Jarrod Moss (partial support: Psychology student obtained PhD in May, 2006).

Publications Supported by Grant

Journal Publications

[1] Olson, J., K. Kotovsky, and J. Cagan, "Team X: A Case Study in the Conceptual Design of Complex Systems," submitted to: *AI EDAM*, 2007.

[2] Olson, J., K. Kotovsky, and J. Cagan, "Simulating Collaborative Design: A Computational Platform for Investigating Structural Interdependence in Team Design," submitted to: *AI EDAM,* 2007.

[3] Olson, J., K. Kotovsky, and J. Cagan, "Forecasting Solution Accuracy of Complex Systems: Direction of Influence," in preparation, 2007.

[4] Moss, J., K. Kotovsky, and J. Cagan, "Expertise Differences in the Mental Representation of Mechanical Devices in Engineering Design", *Cognitive Science*, Vol. 30, No. 1, pp. 65-93, 2006.

Conference Publications

Moss, J., K. Kotovsky, and J. Cagan, "Cognitive Investigations into Knowledge Representation in Engineering Design," *Design Computation and Cognition 2004*, Cambridge, MA, July, 2004.

Olson, J., J. Cagan, K. Kotovsky, "Unlocking Organizational Potential: A Computational Platform for Investigating Structural Interdependence in Design," *Proceedings of the 2006 ASME Design Engineering Technical Conferences: Design Theory and Methodology Conference, DETC2006-99464,* September 10-13, Philadelphia, 2006.

Theses

Olson, J., *The Collective Potential: Achieving Organizational Potential by Design*, Carnegie Mellon University, Pittsburgh, PA, June, 2006. (full support)

Moss, J., *The Role of Open Goals in Noticing Relevant Information in Problem Solving,* Carnegie Mellon University, Pittsburgh, PA, May, 2006. (partial support)

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14. ABSTRACT

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